



Closed-Cycle Hydrogen-Oxygen Regenerative Fuel Cell at the NASA Glenn Research Center— An Update

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Summary

The closed-cycle hydrogen-oxygen proton exchange membrane (PEM) regenerative fuel cell (RFC) at the NASA Glenn Research Center has demonstrated multiple back-to-back contiguous cycles at rated power and round-trip efficiencies up to 52 percent. It is the first fully closed-cycle RFC ever demonstrated. (The entire system is sealed; nothing enters or escapes the system other than electrical power and heat.) During fiscal year (FY) 06 to FY07, the system's numerous modifications and internal improvements focused on reducing parasitic power, heat loss, and noise signature; increasing its functionality as an unattended automated energy storage device; and in-service reliability.

This paper updates the FY06 to FY07 experimental effort and highlights the performance achieved to date. Continuing test operations focus on

- Increasing the performance envelope boundaries
- Improving startup and transition performance
- Operating the RFC as an energy storage device on a regular basis
- Increasing the number of contiguous uninterrupted charge-discharge cycles
- Continuing development of fully automated operation and system health monitoring
- Defining instrumentation and in situ fluid sampling strategies to monitor health and anticipate breakdowns

The RFC has potential as an energy storage device for aerospace solar power systems such as solar electric aircraft, lunar and planetary surface installations, and any airless environment with extended eclipse times (>4 hr) where minimum system weight is critical. Its development process continues on a path of risk-reduction for the NASA's future flight system for the manned lunar outpost.

Background

NASA began development of a closed-cycle hydrogen-oxygen PEM RFC in 1998 under the Aeronautics Environmental Research Aircraft and Sensor Technology (ERAST) project and continued its development to technology readiness level (TRL) 5 (brassboard demonstration of the technology) through FY05 under the Low Emissions Alternative Power (LEAP) project. Development expenditure for the RFC was \$20 million over 8 years (total both projects). Accomplishments included the successful development of lighter weight hydrogen-oxygen PEM fuel cell and electrolyzer stacks, and the creation of an RFC system design traceable to 600 W-hr per kg (ref. 1), followed by a 5-kWe closed-cycle RFC brassboard energy storage system demonstration (refs. 2 to 5). The brassboard demonstration, carried out at Glenn, was for a 12 hr/12 hr cycle consistent with a high-altitude, solar unmanned aerial vehicle operating at tropical latitudes. Testing carried out from 2003 through 2005 demonstrated the following:

- Fully closed-cycle operation (September 2003).
- Closed-cycle operation at rated power of 5 kWe (500 mA/cm² for fuel cell, 1000 mA/cm² for electrolyzer, December 2003). Longest elapsed run was 8 hr.
- Closed-cycle operation at rated power of 5 kWe (500 mA/cm² for fuel cell, 1000 mA/cm² for electrolyzer) under semiautonomous control (automatic operation, with human operator

oversight) through steady-state operation, power level changes and mode transitions (June to August 2004). The longest elapsed run was 21 hr.

- Automatic safety systems operation, no human intervention (September 2003 to July 2005).
- Two complete charge-discharge cycles at full rated power, 70 elapsed hr.
- Uninterrupted closed-cycle operation at full power through five repeated back-to-back contiguous charge-discharge cycles (June 26 to July 1, 2005), for a total of 149 elapsed hr.
- Round-trip efficiencies to 52 percent (July 2005).

The June to July 2005, 5-day demonstration was ended by intentionally shutting down the system, although it was still capable of repeating more charge-discharge cycles. It is the first fully closed-cycle RFC ever demonstrated. (The entire system is sealed; nothing enters or escapes the system other than electrical power and heat.) Figure 1 shows the electrical current and voltage inputs, outputs, and reactant inventory balances that were observed during the 5-day demonstration (ref. 4). This demonstration, while significant as an end-to-end electrochemical and fluid systems feasibility proof, could not yet categorize

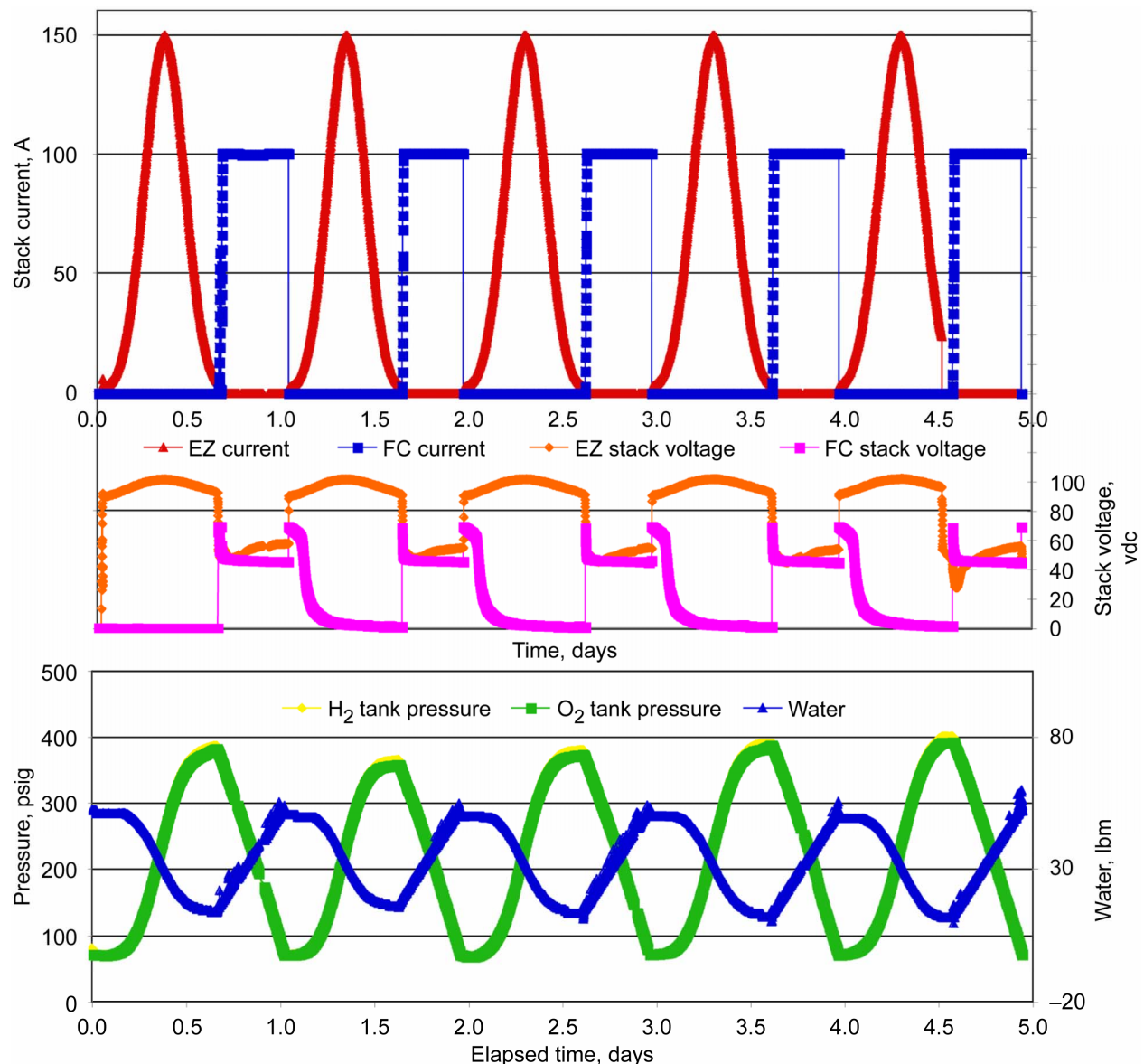


Figure 1.—NASA Glenn RFC 5-day demonstration.

the system as an operational energy storage device, because control was semiautonomous (many, but not all, of the control functions were fully automated), and the reactant recirculation loops were not temperature-stabilized to the degree required for automated operation. The double-acting solenoid recirculation pumps in these loops were also a limiting factor; while they reliably handled two-phase flow, they consumed an inordinate amount of power, made an excessive amount of noise, and tended to wear out quickly.

During operation, the fuel cell recirculation loops required considerable operator intervention to maintain the fuel cell stack at full power. Operator intervention was needed to counteract water droplet blockages that formed in the entry and exit ports of individual electrochemical cells in the stack, and also to reverse the partial flooding and water droplet blockages that often caused individual cells to lose voltage and drop out. This was the most problematic aspect of hydrogen-oxygen closed-cycle operation. The closed-cycle RFC uses pure oxygen rather than air. Compared to hydrogen-air fuel cells, a hydrogen-oxygen fuel cell experiences a much lower cathode mass flow rate for the same current density and water production. Since the oxygen flowing over its cathode is not diluted (as is the case with air), there is not the additional diluent mass flow that aids water removal in the hydrogen-air cell. Generally, there is not enough excess gas flow in the hydrogen-oxygen fuel cell to remove the product water as vapor. As a result, the hydrogen-oxygen fuel cell always has large amounts of liquid water present; the fluid transport mechanisms that convey reactants to the active area and product water away from the active area must contend with large liquid fractions.

The liquid water does not interfere with the electrochemical conversion process, but when trapped in the gas diffusion layer (GDL) or cell ports, it gets in the way of reactants trying to reach the catalyzed surfaces, reducing activity within the cell causing the cell voltage (relative to its neighbors) to drop. Figure 2 shows the stack load current and cell voltages during a test run plagued by water droplets, where individual cells are dropping out and forcing the operator to reduce load current until the blockage has been cleared. The onset of blockage typically occurs within seconds. Clearing the blockage may take tens of minutes, but once it has begun to clear, it takes only seconds.

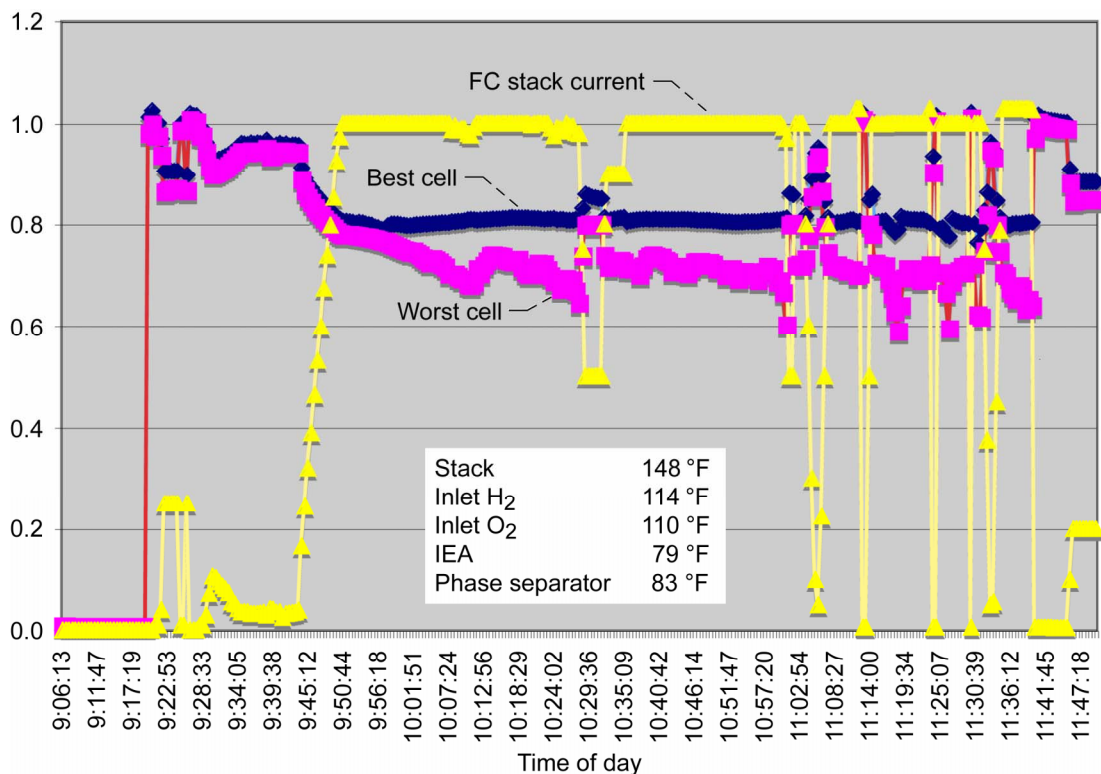


Figure 2.—A test run plagued by water droplets, 6/9/06.

Improvements

In fall 2005, the rig was taken down for service and the double acting solenoid pumps were replaced with newly developed, single-vane rotary pumps. The electric drive units supplied by the manufacturer did not have the degree of low speed control required for accurate stoichiometric flow at low stack current; therefore, it was necessary to develop a more accurate motor speed controller, which depended not only on voltage feedback, but also on Hall effect position sensors within the brushless dc motor. The speed controller had to turn the pump, loaded with two-phase flow, at any commanded rpm from 300 to 3000 rpm, and also be able to reliably restart pump rotation from a dead stop to the commanded rpm.

To compound the problem, the earliest production samples of pumps had manufacturing-tolerance and materials issues, which produced premature wear and affected control repeatability. Over time, these were addressed by the manufacturer, but testing was often curtailed by pump failure. Eventually there was a set of pumps installed that behaved consistently. When properly set up, the single-vane rotary pumps were relatively energy efficient and quiet and exhibited reasonable wear rates.

Fuel cell stacks from two different manufacturers were tested through the spring and summer of 2006. The stack developers, whose experience was mainly with hydrogen-air systems, were emphatic about keeping the reactant inlets at relative humidities above 80 percent to prevent dryout. To accommodate their concerns, Nafion (DuPont) tube humidifiers were sited in both reactant streams immediately ahead of the stack inlets, and each humidifier was cross-connected to its respective stack exit so that the inlet stream was heated and humidified by its respective exit stream. (Figure 3 shows stack inlet and exit connections before and after the humidifiers were added.) The inlet lines leading directly into the stack were also insulated and trace heated to prevent condensation of the humidified gases against the tube walls (prevent inlet water droplet formation).

These improvements produced more stable stack performance (i.e., reduced operator intervention) during prolonged operations, but did not eliminate the sporadic cell voltage instabilities and dropouts. Most problematic were startups from a cold condition where the stack was warming on its way to operating temperature, but the recirculation loop and phase separator plumbing took longer to reach operating temperature. This caused condensation within the recirculation loop and resulted in water droplets that were ingested by the stack.

Cell dropouts were troublesome; once an individual cell became flooded, the stack could no longer maintain rated current because of the flooded cell's voltage drop. The situation would necessitate an

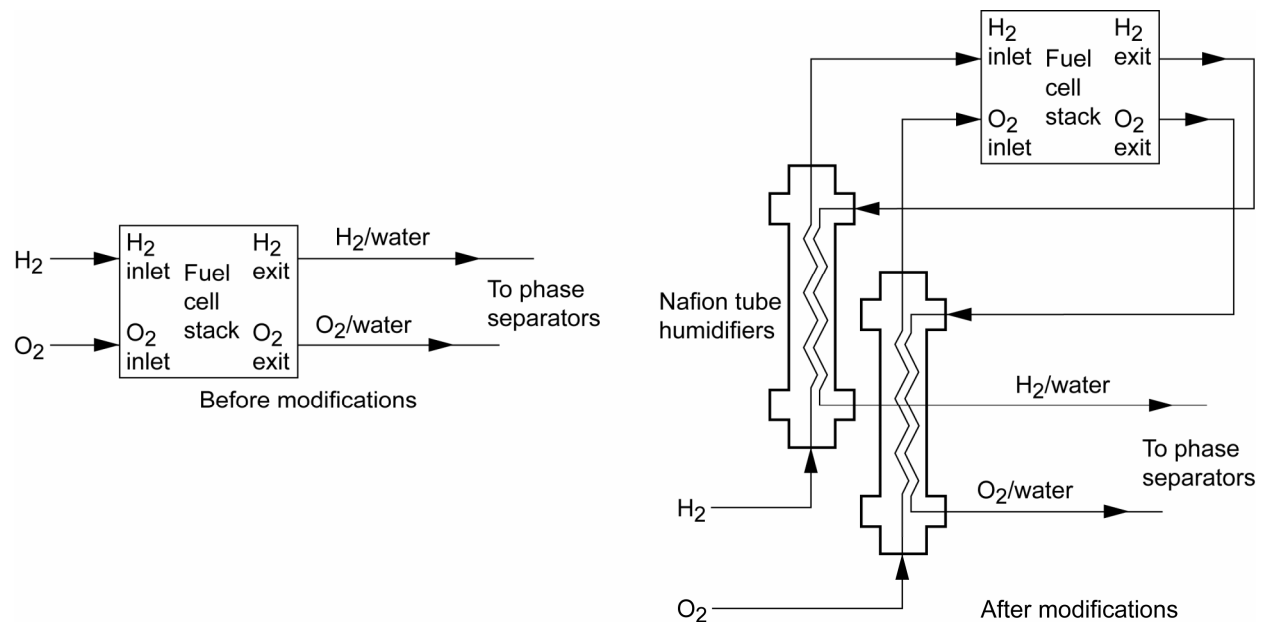


Figure 3.—RFCS reactant stream design modifications.

immediate power reduction, and could be reversed only very slowly, by running the stack lightly loaded with excessive recirculation flow until the liquid blockage was removed. Recirculation flow expressed in “stoichs” refers to the amount flowing compared to what it would be if the reactants in the stream were 100 percent utilized—100 percent utilization would be 1 stoich, no excess flow, 2 stoichs would be 50 percent utilization, 4 stoichs would be 25 percent utilization, and so on. For a hydrogen-oxygen fuel cell stack the typical cathode flow rate is 2 to 3 stoichs.

During these tests it became obvious that cell flooding was the major issue; the cell voltage fluctuations were not caused by dryout or contamination but by flooding as evidenced by the following:

- (1) Periodic impedance testing of the stacks always showed the cells to be well hydrated
- (2) Presence of liquid water in the stack inlet lines whenever the stack was disconnected
- (3) Observed cell voltage fluctuations exhibited a time constant of seconds to 1 or 2 min
- (4) Cell dropouts were rapid in onset and randomly occurring
- (5) Cell dropouts could be reversed by running the stack lightly loaded with excessive recirculation flow (typically over 5 stoichs)
- (6) Dropout reversal was equally rapid (cell voltages would clear within 2 to 3 s)
- (7) Dropout behavior would migrate downstream from cell to cell consistent with water droplet migration
- (8) Cell dropouts during startup could be greatly reduced by evacuating the stack before startup

In fall 2006, steps were taken to address the cell flooding issues

- (1) Remove the Nafion tube humidifier units
- (2) Enclose stacks, recirculation loops and phase separator hardware (integrated equipment assembly (IEA)) within a cabinet
- (3) Heat the IEA enclosure internally with controlled temperature forced air circulation
- (4) Implement more precise temperature control of the fuel cell stack coolant loop

Initially, these improvements were aimed at stabilizing the recirculation loop and phase separator plumbing temperatures through all operating modes including shutdown, keeping them within 20 °C of the stack’s operating point. These steps produced more stable fuel cell performance, but did not completely eliminate the water droplet formation and flooding. Operator intervention would often be required during startup and mode transitions, and occasionally during steady-state operations. Figure 4 shows a typical stack current and voltage versus time profile that was observed during this testing period.

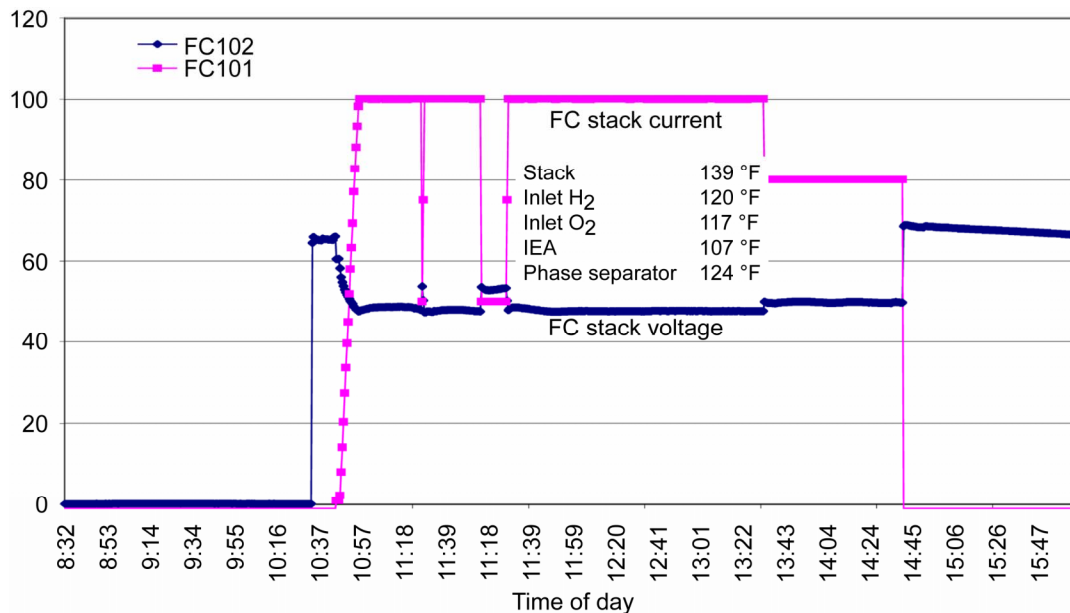


Figure 4.—Fuel cell performance, 10/24/06.

The startup is relatively smooth, but one individual cell starts to drop out after only 25 min, load current is dropped to 50 A and the cell is cleared; 100-A load current is resumed but has to be dropped back again 20 min later when another cell experiences blockage.

Continued testing in late October through November 2006 provided more insight into the water management issues. It became apparent that it would be advantageous to redirect the heated airflow such that the warmest zones within the IEA were the reactant feedlines closest to the fuel cell stack, and to reduce heating to the pump and phase separator areas further away from the stack. In mid-November the forced air heater was repositioned so that the heated airflow was directed towards the reactant feedlines. This step further reduced water droplet formation to the extent that liquid water no longer accumulated in the stack inlet traps, and cell voltages were more stable, over a wider operating range. The redirection appears to have produced a positive “vapor pressure gradient,” which tended to drive water away from the stack, and into the phase separators. The redirection created a thermal gradient, which made the stack the warmest point in the loop; the phase separator reservoirs became the coldest, and a smooth, progressively downward temperature transition between these two points was created. For the fuel cell recirculation loops that operate at roughly constant pressure, the resulting positive temperature gradient, from the stack outwards, gave rise to a vapor pressure differential similar to a heat pipe.

Additional steps were taken in late November and early December 2006. The recirculation pumps were replaced with freshly refurbished units. The stack inlet lines were shortened and the water traps removed. The fuel cell stack was replaced with a unit with more effective temperature control (upgraded from one cooling cell for two electrochemical cells to one cooling cell for every electrochemical cell), and the stack cooling loop's capacity was upgraded. Further software changes were made to implement more precise temperature control of the cooling loop, and to maintain trickle current during fuel cell stack shutdown and isolation and during the recombination phase. The trickle current keeps fuel cell voltages below “open circuit” to prevent GDL carbon corrosion while the stack is unloaded.

Figure 5 shows the overall recirculation loop improvements. These recent changes have improved performance. Beginning in mid-December, the fuel cell stack no longer exhibited voltage fluctuations. During cyclic tests through the end of January, stable operation was achieved to the extent that it was possible to maintain steady-state operation in fuel cell mode with no operator intervention whatsoever. Figure 6 shows a profile of stack current and voltage versus time from this time period, a result of the most recently implemented thermal control. Startup is smooth and the stack remains stable for the entire period. The thermal profile that was created within the recirculation loop maintained a continuous positive vapor pressure gradient from the stack all the way back to the phase separators. With such a profile in place, the system was brought up from cold start to full power in less than 20 min, and maintained at full power as long as the reactant gases lasted.

Because of the significant thermal inertia inherent in this system's stainless steel and water inventory, there are limits on how quickly a smooth transition may be accomplished, and transitions from electrolysis mode or startup still occasionally require the attention of a skilled operator to combat water droplet blockages. Figures 7(a) and (b) show the example of a water droplet occurrence during rapid startup. In figure 7(a) we see the stack current and voltage versus time profile, which is relatively smooth, but figure 7(b) shows that, out of 64 individual cells, 2 of them were affected by blockage. In this case, operator intervention (momentarily ramping up the recirculation rate) was effective, and the cells recovered immediately before load was shed.

The thermal inertia is a limiting factor. In a new design, thermal inertia could be reduced if the IEA had fewer components more compactly arranged, currently the effects of thermal inertia can either be (1) overcome by raising the thermal forcing functions (more powerful heaters and chiller) or (2) accommodated with software changes to increase the control loop time constants (a less expensive solution).

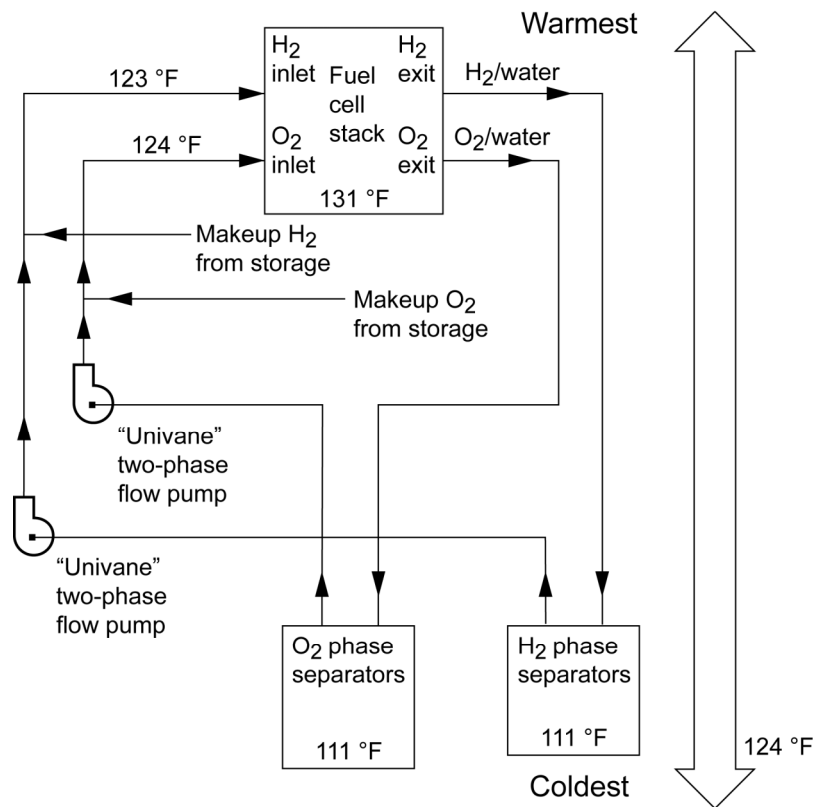


Figure 5.—Reactant recirculation loop thermal gradient.

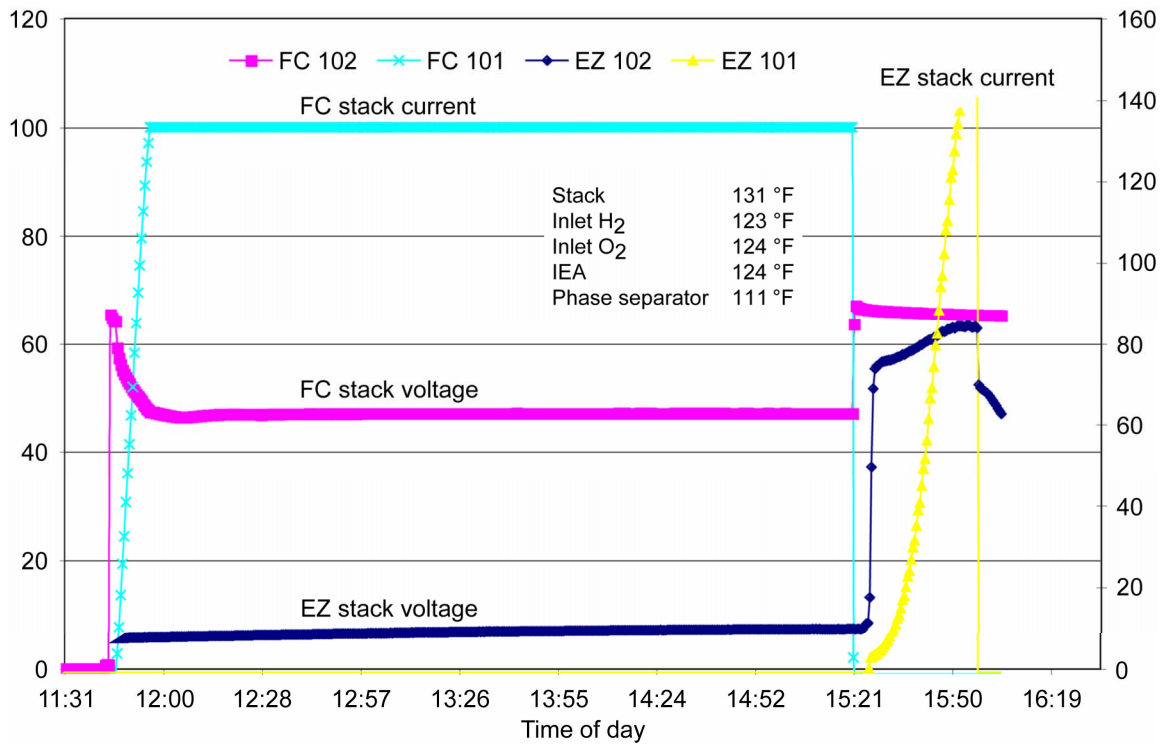


Figure 6.—Stable operation.

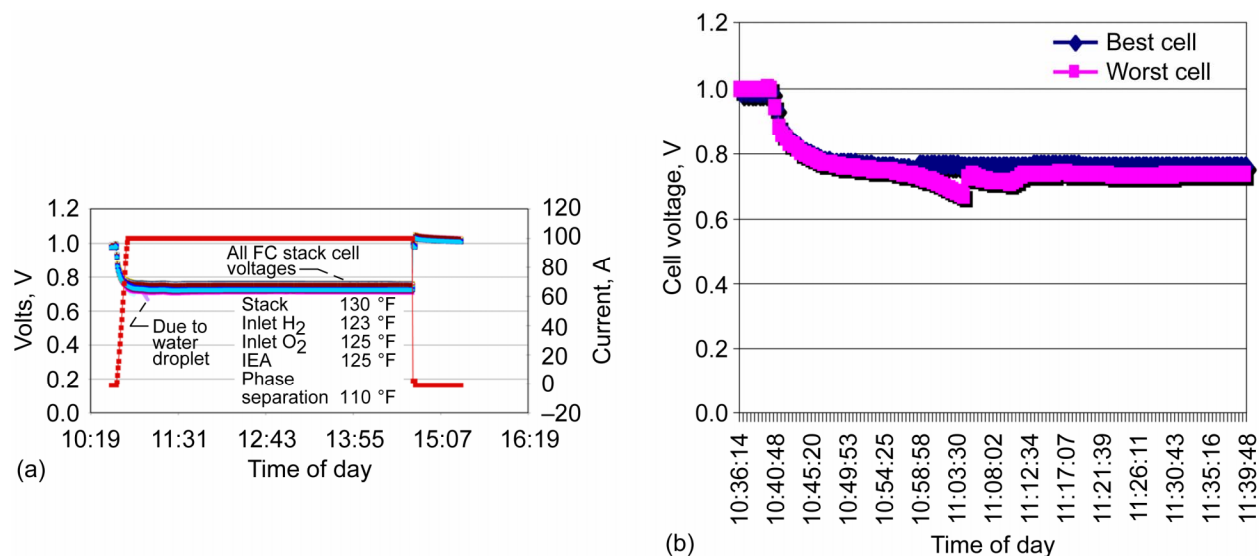


Figure 7.—Water droplet occurrence during rapid startup. (a) Occasional droplet at startup. (b) Occasional droplet at startup.

Future Work

The NASA Glenn Research Center has the world's first fully closed-cycle RFC ever demonstrated, and this demonstration has proven the regenerative system's feasibility and long-term potential. Solar photovoltaic power with a closed-cycle RFC for energy storage has been baselined as the power system for NASA's anticipated manned lunar base (ref. 6). Present consensus within NASA is that another 10 to 15 years will elapse before manned lunar missions are deployed. Solar/RFC technology baselined for these missions would need to be above TRL 6 in about 5 years.

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